

**BUILD AND TEST A NEW TYPE OF COMPRESSOR
FOR STRIPPER WELL PRODUCTION APPLICATION**

2790-WWVC-DOE-2098

**FINAL TECHNICAL REPORT
SEPTEMBER 1, 2004 - DECEMBER 31, 2005**

REPORT DATE: JULY 2006

PAUL WEATHERBEE, PRINCIPAL AUTHOR

**W&W VACUUM & COMPRESSORS, INC.
P.O. BOX 5082
ABILENE, TX 79608**

DISCLAIMER:

“This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibilities for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed or represents that its use would infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.”

ABSTRACT

The aim of this research and development project was to further refine and optimize the Weatherbee compressor design in preparation for selling it as a commercial product. Problems with quality, documentation and cost overruns by the original fabrication vendor caused unanticipated delays and consumed an inordinate proportion of allocated resources. Two alternate vendors were brought on board later in the project to address the shortcomings of the original vendor, which brought significant improvements in design, documentation and quality control. With the help of the new vendors, four 8.5-inch compressors were fabricated and are undergoing testing. A critical element of pump commercialization is seal design. Two seal designs have been tested with successful outcome. We outline below the progress made towards a commercial product.

TABLE OF CONTENTS

PAGE NUMBERS

EXECUTIVE SUMMARY

Executive Summary	1
-------------------------	---

EXPERIMENTAL SECTION - RESULTS AND DISCUSSIONS

Task 1: Test Stand Upgrade	5
Task 2: Manufacture of Compressors	7
Task 3-8: Compressor Optimization and Successive Compressor Builds	14
Task 9: Design for Manufacturability	14

CONCLUSION	15
------------------	----

REFERENCES	15
------------------	----

LIST OF FIGURES

Figure 1: Instrumentation Panel and 6-9" Compressor Test Stand	5
Figure 2: Instrument Panel (Rear View) and 6-9" Compressor Test Stand	6
Figure 3: 4-6" Compressor Test Stand	6
Figure 4: Seal Developed with Parker-Hannifin	10
Figure 5: Seal Shown in Compressor Assembly	10
Figure 6: Southwest Research Institute in San Antonio	11
Figure 7: 8.5-inch Compressor, Shown with Top Housing Removed	12
Figure 8: Preliminary Performance Data of 8.5-inch Compressor	13
Figure 9: Preliminary Performance Data of 4-inch Compressor	13

EXECUTIVE SUMMARY

The aim of this research and development project was to further refine and optimize the Weatherbee compressor design in preparation for selling it as a commercial product. This was to be accomplished through a series of tasks ranging from the analytical evaluation of the mechanical integrity to maximizing the efficiency through CFD to streamlining the design for manufacturability. Unfortunately, unexpected obstacles, primarily in machining, fabrication, and developing seals, prevented us from fully realizing our original goals. While we did not attain all of our original objectives, we feel that the progress made and lessons learned in this development effort will greatly aid our progress towards a commercial product.

The Phase II proposal divided the development effort into a series of tasks designed to optimize performance and ready the compressor for commercial production. These tasks consisted of first upgrading the existing compressor test stand to provide improved capability to characterize compressor performance. The successive tasks consisted of alternating building compressor prototypes with analyzing and optimizing design parameters. The objective of the first compressor prototype was to incorporate the lessons learned in Phase 1 of the project and provide a baseline for later designs. Subsequent to this, computational analysis on the structure and fluid dynamics was to be performed to optimize the compressor for strength, weight, and operating efficiency. Next, the compressor seals would be optimized by incorporating the proposed seal designs into analyses and testing. Lastly, a study of manufacturability would optimize the compressor from manufacturability and cost standpoint.

Unfortunately, the project was ambushed by problems that impeded the execution of the above stated development scheme, primarily due to issues with the manufacture of the compressors. The challenges were such that nearly all the resources associated with this grant were spent trying to procure quality manufacturing of compress components. Consequently, the finite element and computational fluid dynamic analyses were not performed.

At the onset of the project, Athena Manufacturing was selected based on their advertised machining capabilities. Six 4-inch compressors were designed and machined at Athena. The quality of these compressors, specifically related to tolerance issues, was unsatisfactory. Further investigation revealed problems with design documentation, revision control and management's level of understanding of relevant technical issues. Significant time and resources were lost due to the problems at this vendor.

Although it was difficult to switch vendors partway through the project, a backup machine shop, SPM, was selected to build four 4-inch compressors. Due to the poor documentation control at Athena, SPM was required to re-create the CAD solid models and fabrication drawings. We planned to order the compressors in two sets so we could examine the quality of two compressors prior to placing the order for the remaining two pumps. However, the vendor tripled the price of the second set and as a consequence we did not order the final two compressors.

To provide parallel capability, a third machine shop, Rogers Machining, was approached which had been utilized prior to Grant #1. They were requested to build modified versions of previously built 8.5-inch compressors.

Seals were designed in conjunction with Parker-Hannifin, C. Lee Cook, and Busak & Shamban. Developing the seals has been unexpectedly problematic. Two seals designs from Parker-Hannifin and one from C. Lee Cook were incorporated into the 4-inch compressors; all were unsuccessful at properly sealing the compressors. Currently we are collaborating with Busak & Shamban and Southwest Research in San Antonio to develop seals that will meet the unique requirements of the spherical compressor.

Ultimately, eight 4-inch compressors were manufactured, though the six manufactured by Athena were not considered acceptable to test. Additionally, four 8.5-inch compressors were also fabricated, and are undergoing testing. While the optimization steps outlined in the proposal were not executed, significant working knowledge of the manufacture of these compressors was developed during the course of this grant.

EXPERIMENTAL SECTION - RESULTS AND DISCUSSIONS

The aim of this research and development project was to further refine and optimize the Weatherbee compressor design in preparation for selling it as a commercial product. The Phase II proposal divided the development effort into a series of tasks designed to optimize and ready the compressor for commercial production. The tasks were as follows:

1. Task 1 of the project requires upgrading of the existing compressor test stand to include the following: 4 turbine flow meters with signal conditioners, 4 pressure transducers with excitation sources, a PC with data acquisition board and software, and a servomotor with amplifier and controller.
- 2.* Task 2 of the project requires construction of eight (8) prototype compressors to be built in four stages over the course of the project.
3. Task 3 of the project is to perform a finite element analysis (FEA) to evaluate the current design and thereafter consider appropriate improvements.
4. Task 4 of the project is to perform a computational fluid dynamics (CFD) analysis to simulate fluid flow through the compressor.
- 5.* Task 5 is Prototype Compressor Manufacture (2nd 2 of 8) incorporating into the compressor design the analysis and testing results to date for analysis verification and additional testing.
6. Task 6 requires that the current seal designs be included in the FEA and CFD analyses, combining actual test results with the mathematical analysis to form a basis for seal optimization.
- 7.* Task 7 will utilize the analysis and testing results to date and two evolutionary prototypes (3rd 2 of 8) will be manufactured for seal design verification and additional test, including field tests.
8. Task 8 is to comprehensively update the compressor design based on the optimization efforts described in the previous 7 tasks.
- 9.* Task 9 is to manufacture the remaining two prototype compressors using the updated design from the DFM effort.
10. Task 10 was to compile data and summaries of results collected during above tasks.

* Tasks 2 and 5 included building and bench testing two prototypes each; Tasks 7 and 9 included building, bench testing as well as field-testing.

Due to complications throughout the development process, the optimization tasks and fabrication of the successive prototypes were not performed. Manufacturing capability of the chosen vendor proved to be much weaker than initially perceived. Nearly all the resources of the project were exhausted obtaining fabrication of functional compressors. Although we did not complete all the steps of the development process that we had originally intended, we feel that the lessons learned throughout this project will prove invaluable as we move towards a commercial project.

Without spending undue time making excuses, we would like to outline the details of the experience we had in manufacturing the compressors. We feel it is important to detail this, not only to understand how the project resources were utilized, but also to facilitate appreciation of the knowledge that was gleaned throughout the process.

Task 1: Test Stand Upgrade

Task 1 has been completed successfully with the exception of the purchase of the control software. The test stand in Grant 1 has been upgraded to include 4 turbine flow-meters with signal conditioners and 4 pressure transducers with excitation sources, and a servomotor with an amplifier and controller. The flow-meters are outfitted with a FC-22 flow computer from Omega for displaying and recording flows. The PC with data acquisition board has been acquired. Labview, the data acquisition software, has not yet been purchased.

There is one test stand for each of the two ranges two ranges of compressors, 4-6” and 6-9” and a common instrumentation panel. The 4-6” Compressor Test Stand is outfitted with a 10 Hp Motor and the 6-9” Compressor Test Stand has a 25 Hp Motor. Figure 1 and Figure 2 shows the Instrumentation Panel and the 6-9” Compressor Test Stand. Figure 3 shows the 4-6” Compressor Test Stand.



Figure 1: Test Stand Upgrade: Instrumentation Panel and 6-9” Compressor Test Stand



Figure 2: Test Stand Upgrade: Instrument Panel (Rear View) and 6-9" Compressor Test Stand



Figure 3: Test Stand Upgrade: 4-6" Compressor Test Stand

Task 2: Manufacture of Compressors:

In Grant #1, Athena Manufacturing of Austin, Texas was selected from among several interviewed as the most apparently qualified, based on the presence of a state-of-the art facility, ISO 9001 compliance and anticipated registration in December 2004, an engineering staff, and machining experts with proficiency in all phases of computer-based machining technology.

In Grant #1 the 8.5-inch compressor design was to be reduced to a 4-inch version. The 4-inch compressor was anticipated to cost less in materials and machining time and to be easier to work with. There were to be two different kinds of seals designed for the 4-inch compressor - a fluid seal and a mechanical seal.

For more details of Grant #1, please see the corresponding final report.

Athena Mfg. was the machine shop used in Grant #1 and for the first six months of Grant #2. Approximately six compressors were built at Athena, but all of them failed. Progress and the major difficulties encountered are outlined below.

1. **CAD/CAM.** Athena used Solidworks software to create a 3-dimensional model of the 4-inch compressor and the associated manufacturing drawings. The model and drawings were used to generate tool-paths and program the automated manufacturing machines. Athena encountered unanticipated problems converting the Solidworks drawings, resulting in off-spec parts.
2. **Machining Tolerances.** Upon investigation, it was determined that parts were not machined to specified tolerances. The effect of these out-of-spec tolerances was greatly magnified in the assemblies, where cumulative tolerances became quite pronounced. A few prototypes were made but the sub-component machining tolerances were so poor that the prototype compressors were out of balance and the bearings did not fit properly, among other issues. We lost a lot of time trying to modify and make these poorly made parts work even though we knew they were not built to specifications.
3. **Revision Control.** Upon further investigation, it was discovered that design changes were not dated and that shop floor modifications to printed drawings were not communicated back to engineering personnel for update on computer versions of those drawings. As a result, it was impossible to determine which versions of the drawings were the most up-to-date. Additionally, the tolerancing method used to fabricate and inspect the parts was insufficient to guarantee successful assembly and operation. For example, if the compressor vane was manufactured to the lower limit of its tolerance band and the housing machined to the upper limit of its tolerance band, then the resulting clearance would be too large for the compressor to properly function. Conversely, if the opposite were true, the parts would interfere with each other. This inherent inadequacy of conventional tolerancing is what led to the incorporation of Geometric Dimensioning and Tolerancing into the compressor design as discussed in Task 9.
4. **Turnover.** It was additionally discovered that this vendor had a large turnover

employees, to the point that continuity was made difficult if not impossible. After numerous meetings and consultations, it was determined that a change in machine shops had to be made.

5. **Management Understanding of Relevant Technical Details.** The shop owner, although highly educated in engineering, did not know in detail how his machining equipment worked, and had to rely on his ever-changing staff to accomplish each task. This magnified the above problems.

We continued well into Grant 2, expecting that accumulated experience and internal controls would lead to resolving the above problems. Unfortunately, this did not happen, and the problems persisted. In all, with the first machine shop, we built about 6 compressors; none of which ran well enough to test. We came to the realization that although Athena had state-of-the-art equipment, they simply were not adequately staffed and organized to complete the project. In March of 2005, we decided to change machine shops.

We switched to SPM Inc, of Round Rock, TX, as our machine shop of choice. They had previously been our second-choice candidate during the selection process related to Grant I. Because the drawings transferred from Athena to SPM were not kept up-to-date, all the CAD design data had to be re-entered. All the compressors and parts that had been manufactured at Athena Mfg., as well as all drawings, were transferred to SPM. We jointly concluded that due to the revision control and machining tolerance problems mentioned above, it would be quicker and easier just to start over. At this point, 7 months into Grant #2, we were starting over as far as design and build were concerned.

SPM initially estimated 2 months to rebuild the 3D solid model and dimensioned drawings, and another 3 months to produce two 4-inch compressors. If the quality of these two compressors was deemed acceptable, they agreed to produce an additional two pumps within 1 month at the same price. In reality, it was a full 3 months before the drawings were completed and 4 months to build the first compressor and another month to finish the second. When the second set of pumps was ordered, SPM was unable to honor their agreement of purchase price. An outside vendor that SPM had used to build the pump housing had received a large contract that exhausted their production capacity. Consequently, the vendor increased the price of the housings from \$1000 to \$10000, effectively doubling the final cost of the compressor.

Concurrent with the change in machining vendor, a quality control scheme was implemented by us where all parts manufactured by SPM are sent to a third machine shop, Rogers Manufacturing in Mineral Wells TX. Jim Rogers had worked with W&W in the past and had expertise in building 8.5" compressors from aluminum along with the manufacturing methodology unique to this compressor. Jim performed quality control inspections on every part manufactured by SPM, inspecting each part against design specifications, and inspected subassemblies to determine whether stack tolerances were met; thereby determining whether a part is then ready to be inserted into a final, assembled compressor prototype. By implementing this new method, we are now getting good quality parts and good compressor assemblies.

After the quality was determined by Rogers Machining to be acceptable for 29 pieces, or 4 compressors, SPM sent these pieces to be nitrided but failed to have them stress relieved prior to nitriding. The heat from nitriding process warped all 29 pieces. It is common practice to stress relieve components undergoing high temperature post processing by heating the material to the temperature that will be encountered during the post processing prior to making the final machining cut. This critical step was entirely missed so that when the parts were heated to 900°F during the nitriding process, they were warped considerably. Despite this warping, there were enough parts that were salvageable through rework to assemble two complete compressors.

We contracted with Rogers Machining to build four 8.5” compressors. The 8.5” compressors were built in lieu of the 5” compressors planned in the Phase II proposal since we had experience with the larger compressors and did not want to suffer further setbacks to the schedule. We encountered one primary hindrance while manufacturing the compressors that resulted from incorrectly altering the casting molds, which were originally designed for aluminum, for steel. The first compressor vanes were not large enough to allow the secondary machining necessary to achieve the demanding compressor tolerances. The molds were corrected and all the compressor components have been produced successfully.

Due to the problems with the machine shops, data transfer and warped parts, we fell behind approximately 6 - 8 months in our schedule. We requested and were given a 4 months extension on the grant.

Seal Design

Designing functioning seals for the Weatherbee compressor has also seen unexpected problems. Multiple designs have been tried without success.

Parker-Hannifin in Salt Lake City designed the first set of seals for the 4-inch compressor. These initial seals did not have adequate preload to prevent air from leaking through.

The second iteration of seals from Parker-Hannifin took a considerable amount of time to acquire. The new design took approximately 4-5 months to develop. This considerable lead-time was due mainly to the unresponsiveness of Parker-Hannifin. The primary issue seemed to be the inability to garner enough attention at the corporation due to the lack of production volume. Countless hours were spent trying to contact them over the phone and even in person with little or no results. Ultimately, we were successful in getting another seal designed and manufactured. However, although these seals function better than the first iteration, they do not meet the necessary performance criteria.



Figure 4: Seal Developed with Parker-Hannifin



Figure 5: Seal Shown in Compressor Assembly

Parallel to the Parker-Hannifin effort we developed seals with C. Lee Cook, locating in Bowling Green Kentucky. Despite difficulty establishing a non-disclosure agreement, we eventually produced a set of seals. The first iteration was too tight to run properly. The seals were then re-machined and fitted into the 4-inch compressor. These seals are currently being tested, but early testing indicates that they are also lacking the desired performance characteristics.

Currently we are collaborating with Busak & Shamban, located in Fort Wayne, Indiana and with Southwest Research Institute to develop seals that will meet the unique requirements of the spherical compressor. Southwest Research Institute is one of the world's foremost independent research and development organizations and is located on 1200 acres in San Antonio, Texas. SWRI uses multidisciplinary approaches to problem solving the engineering sciences and provides R&D services to industry, business and government.



Figure 6: Southwest Research Institute in San Antonio

-

Results from Task 2

At the end of the manufacture process, we had two functioning 4-inch compressors and four 8.5-inch compressors. Figure 7 shows one of the 8.5-inch compressors, partially assembled.

Although complete performance characterization of the compressors has not yet been executed, preliminary test results are shown in Figure 8 and Figure 9 on page [15](#).



Figure 7: 8.5-inch Compressor, Shown with Top Housing Removed

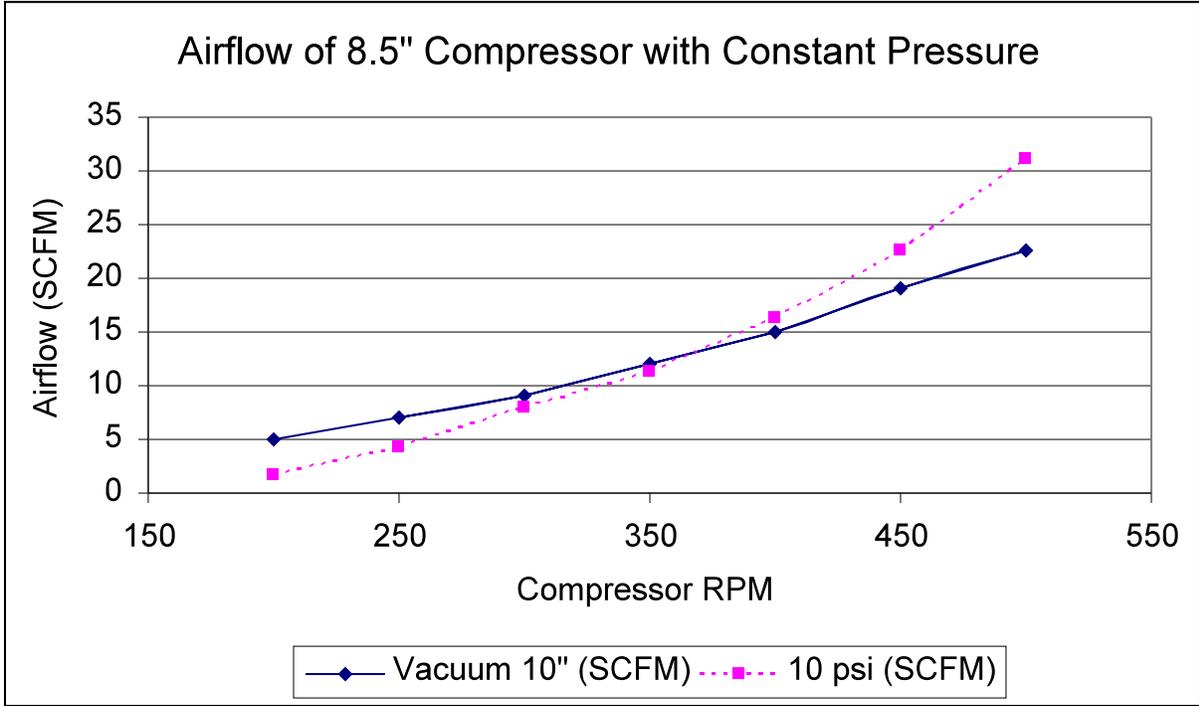


Figure 8: Preliminary Performance Data of 8.5-inch Compressor

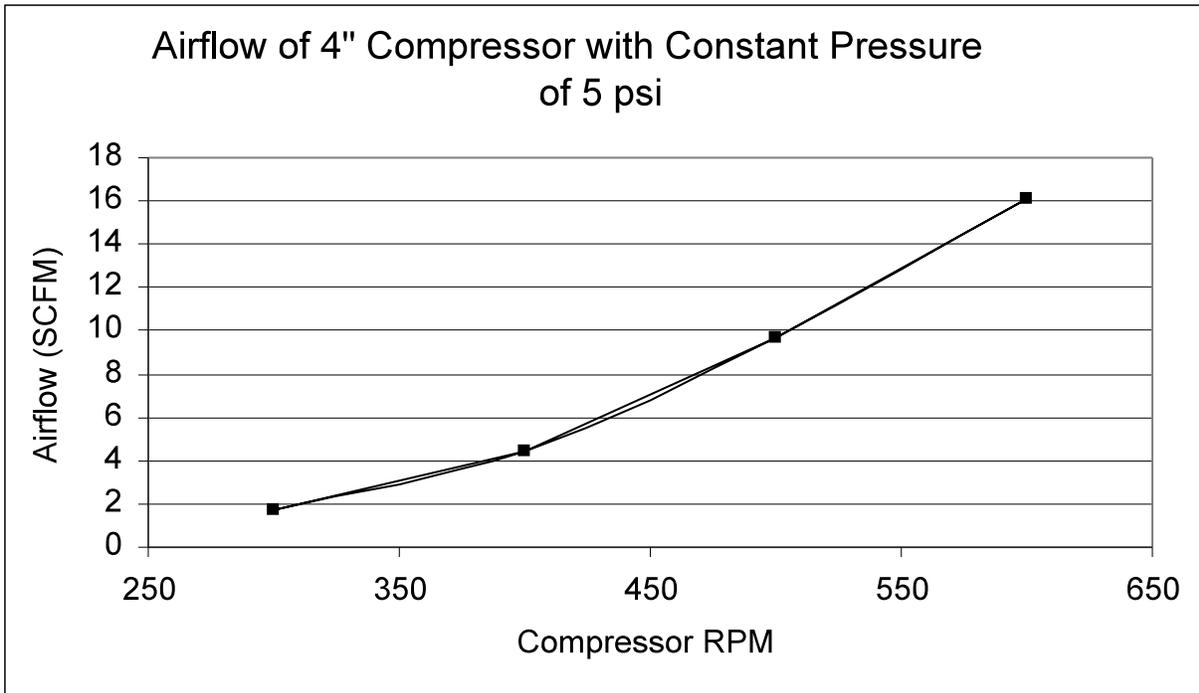


Figure 9: Preliminary Performance Data of 4-inch Compressor

Tasks 3-8: Compressor Optimization and Successive Compressor Builds

Tasks 3-8 consisted of alternating performing analytical optimization steps with building compressor prototypes. Computational analysis on the structure and fluid dynamics was to be performed to optimize the compressor for strength, weight, and operating efficiency. Next, the compressor seals would be optimized by incorporating the proposed seal designs into analyses and testing.

Unfortunately, the issues encountered during task 2, the compressor manufacture, exhausted both time and monetary resources of the project and impeded the execution of the remaining tasks. The finite element analysis and computational fluid dynamic analyses were not performed.

Task 9: Design for Manufacturability

Throughout the design and manufacturing process, the compressor was examined and optimized for manufacturability. One vital milestone reached in this effort was the incorporation of Geometric Dimensioning and Tolerancing (GD&T) into the fabrication drawings. After encountering the aforementioned problems throughout the manufacturing process, we realized that a more exacting method of communicating the critical design parameters was needed. GD&T provides this necessary control.

Geometric tolerancing is an exact language that enables the designer to completely convey their intent. By providing uniformity in drawing specifications and interpretation, GD&T reduces controversy, guesswork, and assumptions throughout the manufacturing and inspection process. GD&T is used to ensure that mating components always fit as planned. Instead of just specifying a certain length between edges or features, GD&T controls the entire surface profile. By incorporating this tool, we can ensure that pieces made from different sources will properly match. The application of this tolerancing scheme to the Weatherbee compressor is an important step towards higher volume production.

Conclusions:

Despite challenges encountered during the manufacturing process, two 4-inch and four 8.5-inch compressors were manufactured and are undergoing initial testing. While the optimization steps outlined in the proposal were not executed, significant working knowledge of the manufacture of these compressors was developed during the course of this grant.

Specific examples of the achievements and knowledge attained in this project include:

- The incorporation of Geometric Dimensioning and Tolerancing in the fabrication drawings
- Understanding of the equipment necessary to manufacture the compressors
- Realizing the utility of, and establishing a third party quality control inspection
- Established relationships with seal vendors and development and testing of multiple seal variations
- Development of nitride process that does not warp components

The practical knowledge gained throughout this project will be instrumental as we move into the commercial production of these compressors.

References:

None.